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Coal use embodied in globalized world economy: From source to sink through supply chain

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ABSTRACT

An empirical analysis of coal use embodied in the globalized world economy is performed in the present work via the application of a systems multi-regional input-output model for 2012. The use of primary coal is tracked from the sources of exploitation to the sinks of final use through inter-regional trade as a global supply network. Mainland China is revealed to be the largest coal user, but the per-capita coal use embodied in its household consumption is only a quarter of that in the United States, and doesn't even exceed the level in the United Kingdom, the leader in the movement away from coal. The global trade volume of coal use is in magnitude calculated up to seventy percent of the world total coal exploitation. The United States is demonstrated to be the world's leading importer of coal use, of which the imports are dominated by non-coal products as indirect coal imports. In contrast, mainland China is the leading exporter, mainly due to the massive exports of commodities 'Made in China'. Two new indicators of self-sufficiency rates are developed, in order to explore the direct and indirect external coal dependence of the region. Two-fifths of the coal finally used by the United States turns out to be exploited from foreign areas, which is different from the result that the United States has no dependence on foreign coal resources based on the conventional external dependence degree. This overview of coal use aims to provide a global insight into energy sustainability, as well as a sound scientific reference for policy making for global resources management and climate change mitigation.

1. Introduction

Coal is one of the most basic energy resources around the world. Its earliest utilization in human history can be traced back to 1500 BCE when this black resource was firstly discovered in China [1]. But it was not until the Industrial Revolution of the 18th and 19th centuries that the large-scale excavation and extensive use of coal resources were carried out worldwide. Coal served as the dominant fuel to run the new industries during that period of technological reformation. The market for coal was therefore greatly expanded, and has continued to grow ever since, with occasional temporary fluctuations [2]. Nowadays, coal still plays a vital role in the world's primary energy mix. In 2015, coal provided 29% of global primary energy needs, 41% of the world's electricity, and an essential input into 44% of the world's industry production [3,4]. Because of the low cost and wide availability, coal's role is expected to remain at the similar level over the next 20 years [4].

However, with the widespread coal use, the environmental pollution caused by coal mining and combustion has become an increasing concern [5]. Issues such as fog and haze, acid rain, and groundwater contamination have long been linked to coal. What's more, coal has a relatively high carbon content, and coal consumption is now regarded as the leading source of anthropogenic greenhouse gas emissions causing global warming threat [6]. In 2014, coal-related CO_2 emissions reached 15 Gt, nearly half of global total emissions [7]. The use of coal has therefore become the focus of both energy and environmental strategies, and has attracted an enormous amount of research attention.

Previous researches on coal have contributed significantly to facilitating people's understanding of this resource from various aspects, including its regional consumption [8,9], optimal management [10,11], market transactions [12,13], environmental disadvantages [14,15], policies and regulations [16,17], and so forth. However, those studies were confined to the direct coal use, the direct coal trade and the direct pollution induced by the direct coal use. With regard to the indirect coal use or trade, i.e., the consumption or transaction of commodities and services that require coal inputs in their production processes, few studies have ever given due consideration [18,19]. Coal as a basic natural resource provides numerous industries with energy

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Nomenclature

BCE	before common era
CO_2	carbon dioxide
IOA	input-output analysis
IEA	International Energy Agency
ASEAN	Association of Southeast Asian Nations
EU	European Union
ROW	rest of world

Formulae

z	sectoral exchanges for intermediate use
f	sectoral exchanges for final use
d	sectoral direct coal exploitation
ε	sectoral embodied coal intensity
o	sectoral total output
Z	matrix form of z
F	matrix form of f
D	matrix form of d
E	matrix form of ε
O	matrix form of o
CEF	coal embodied in regional final use
CED	coal exploited directly by region
CCD	coal consumed directly by region
CEI	coal embodied in regional imports
CEE	coal embodied in regional exports
CEB	coal embodied in regional trade balance
γ	self-sufficiency rate

and material support, and considerable amounts of indirect coal use is hidden in these industrial products and services. For example, a telephone requires electricity during its manufacturing course, while coal in some countries, like China, is the major fuel for the generation of electricity. Coal is therefore indirectly used by the telephone made in China. As a matter of fact, many high-income nations get a decline in domestic coal use and carbon emissions through importing coal-intensive goods and services from the middle- and low-income areas. With the aid of international trade, those net-importing countries successfully transfer the pressures on resources and environment to the foreign regions [20,21]. This transfer phenomenon is becoming increasingly prominent in the present globalization, and is likely to mislead the allocation of national responsibility in international cooperation for resource conversation and environmental protection. Hence, it is imperative to comprehensively explore the indirect coal use embodied in the global commodity and service flows.

The indirect effects have been emphasized previously regarding energy use [22,23], greenhouse gas emissions [24–26], freshwater consumption [27–29], land occupancy [30,31], mercury pollution [32], etc. Typically, Lenzen et al. [33] provided an energy evaluation for the city of Sydney, and showed that the indirect energy consumption in Sydney was 2.3 times of the direct energy consumption. A similar ratio can also be found in another report on the energy use of Macao, China [34]. For the European Union overall, Steen-Olsen et al. [35] pointed out that 43% of its total carbon emissions, 47% of total land use and 52% of total water consumption occurred indirectly because of the internal and external trade. According to Wiedmann et al. [36] on raw material consumption of the whole world, the indirect trade volume of materials and products is presented in magnitude twice larger than that of the direct physical trade. It can be seen that the indirect effects are now playing an even more important role than the direct ones. Given the unique status of coal in both energy and environmental fields, this work aims to present a systematic overview for both the direct and indirect coal use in the world economy by means of the embodiment analysis for the first time.

The embodiment analysis has its origin in the theory of systems ecology [37,38], and has been extensively applied to reveal the systems energetics. A well-known concept is the embodied energy, which is defined as the total (direct plus indirect) primary energy inputs to generate and sustain a product or service [39]. Here, this concept is specialized for primary coal as total coal embedded in the product or service, which can be termed as embodied coal, parallel to the terms of embodied oil [40], embodied solar energy [41] and embodied nuclear energy [42] in previous studies. For the economy, coal is essentially an exogenous primary resource from the environment [43]. To obtain the utility of coal to maintain the economic system, human beings exploit coal resource from the environment. From the perspective of systems ecology, this resource is used once it is exploited because the resource leaves the environmental system at the point. Then in the economic system, the utility of coal is embodied in various goods and services and consumed by the final use activities. In this regard, the present research of embodied coal is conducted based on coal exploitation from the environment for the economy in terms of coal's economic use, which is different from the previous embodiment analyses focusing on coal's technological consumption, i.e., the combustion of coal [44,45]. Here coal use embodied in the world economy is overviewed and the coal use flows embodied in the inter-regional trade are tracked from the source of exploitation to the sink of final use, to make an inclusive world coal budget.

2. Methodology and data

2.1. Multi-regional input-output model

The input-output analysis (IOA) is acknowledged to be a useful top-down technique to underpin the embodiment accounting. The input-output tables document the interactions between industries within an economic system, and thus enable us to trace both the direct and indirect effects through the complex trade exchanges [46,47]. Since the original introduction of IOA to economic simulation in 1936 [48], it has induced vast attention in the academic field and many related models like single-regional IOA [49,50], multi-regional IOA [51–53] and inter-regional IOA [54–56] have been proposed. As an improvement of single-regional IOA by distinguishing between domestic and foreign production technologies, and a simplification of inter-regional IOA dealing with data limitations, multi-regional IOA shows a significant advantage to describe the world economy, and finds broad application to embodiment studies [57].

In recent years, a systems multi-regional IOA model is developed based on the embodiment concept in the systems ecology, in terms of the biophysical balance that total resources use induced by total outputs equals exogenous resources inputs plus resources embodied in intermediate inputs [58]. This model pays equal attention to the intermediate use and the final use as two basic components of the total output. The ecological endowments flows associated with both the two components can therefore be depicted to help perceive the complete picture of how resources or emissions flow within the system. So far, this model has been applied to numerous systems, including industrial production systems [59–61] and economic systems at regional [62,63], national [64,65] and global [66–68] scales. In the present paper, the systems multi-regional IOA is adopted for a systematic analysis of coal use by the globalized economy.

2.2. Algorithm

The world economy is considered as a m-region, n-sector coupled network. For each sector in each region as an individual entry, the

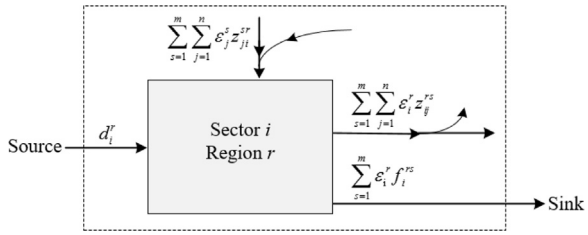

Fig. 1. Embodied coal flows for a typical sector in world economy.

embodied coal flows can be portrayed in Fig. 1.z_{ij}^{rs} ($r, s \in \{1, 2, \ldots, m\}$, $i, j \in \{1, 2, \ldots, n\}$) is the monetary value of the goods or service sold by Sector i in Region r as intermediate input to Sector j in Region s, and f_i^{rs} is the monetary value of the goods or service from Sector i in Region r to Region s for final use. Final use represents the end of the production cycle and the goods and services used for final use no longer appear in the economic system. Hence, final use is regarded as the sink of embodied coal use in this study. As the exploitation marks the beginning of embodied coal use as the source, d_i^r is defined specifically as the amount of coal exploited directly by Sector i in Region r from the environment. Moreover, ε_i^r denotes the embodied coal intensity of the goods or service of Sector i in Region r, which implies the average amount of direct plus indirect coal use to produce one unit of goods or service by this sector in the existing technology. The biophysical input-output balance equation for embodied coal use in the sector can therefore be formulated as

$$d_i^r + \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s z_{ji}^{sr} = \varepsilon_i^r o_i^r \tag{1}$$

where o_i^r refers to the monetary value of the total output of Sector i in Region r, equal to the sum of outputs for intermediate use $\left(\sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs}\right)$ and final use ($\sum_{s=1}^{m} f_i^{rs}$). Linking all balance formulae for the $m{\cdot}n$ sectors, the above equation can be expressed in a matrix form as

$$D + EZ = E\hat{O} \tag{2}$$

in which $D = [d_i^r]_{1\times(m\cdot n)}$, $E = [\varepsilon_i^r]_{1\times(m\cdot n)}$, $Z = [z_{ij}^{rs}]_{(m\cdot n)\times(m\cdot n)}$, and $O = [o_i^r]_{1\times(m\cdot n)}$($\hat{O}$ is the corresponding diagonal matrix). With properly given direct coal input inventory (D), trade data between sectors (Z) and total sectoral output (O), the embodied coal intensity (E) can be obtained.

Thereafter the embodied coal in concerned economic flows can be analyzed based on the sectoral intensity. The coal embodied in Region r's final use (CEF^r) is acquired by

$$CEF^r = \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s f_j^{sr} \tag{3}$$

In contrast to CED^r ($= \sum_{i=1}^{n} d_i^r$), which is defined as the total coal exploited directly in Region r to enunciate the direct coal requirements of Region r as a source in coal supply chains, CEF^r records the total coal requirements of Region r as a sink.

In order to reflect the region's trading pattern, the traded embodied coal fluxes of coal embodied in the imports (*CEI*), exports (*CEE*) and trade balance (*CEB*) are separately presented as

$$CEI^r = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}\left(\sum_{i=1}^{n} \varepsilon_j^s z_{ji}^{sr} + \varepsilon_j^s f_j^{sr}\right) \tag{4}$$

$$CEE^r = \sum_{s=1(s\neq r)}^{m}\sum_{i=1}^{n}\left(\sum_{j=1}^{n} \varepsilon_i^r z_{ij}^{rs} + \varepsilon_i^r f_i^{rs}\right) \tag{5}$$

$$CEB^r = CEI^r - CEE^r \tag{6}$$

2.3. Coal security indicators

In the global coal supply chains, different regions represent different sources for coal production. In order to differentiate between these sources, the coal resources are classified into m groups by the region where the resources are exploited. Corresponding to the direct coal input matrix D discussed above, a new matrix $D' = [d_j^{rs}]_{m\times(m\cdot n)}$ is formed, in which d_j^{rs} is defined as the amount of Region r's coal resources that are exploited by Sector j in Region s. As coal resources are regarded as the natural treasure owned by local regions, $d_j^{rs} = 0 (r \neq s)$. Substituting D' for D in Eq. (3), the embodied intensity matrix can be rewritten as $E' = [\varepsilon_j^{rs}]_{m\times(m\cdot n)}$. ε_j^{rs} evaluates the requirements of coal resources from Region r to produce one unit of goods or service in Sector j, Region s. By contrast, ε_j^s elucidates the total requirements of coal resources from all the m regions, that is, $\varepsilon_j^s = \sum_{r=1}^{m} \varepsilon_j^{rs}$.

Region r as a source, exploits coal resources from local environment, and provides these resources for its own or foreign regions' final use. Consequently, a self-sufficiency rate of the source region can be defined as the ratio of the coal exploited locally for its own final use over the total coal exploited locally (Eq. (7)). Analogously, for Region r as a sink, many coal resources are required for its final use. These resources can be divided into two parts: one is provided by local environment, and the other is exploited in foreign regions. Hence, the share occupied by the former part is proposed here as the self-sufficiency rate of the sink region to assess the contribution of local coal resources to its final use (Eq. (8)). The two rates together quantify the region's coal security.

$$\gamma_{source}^r = \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^{rs} f_j^{sr} / CED^r \tag{7}$$

$$\gamma_{sink}^r = \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^{rs} f_j^{sr} / CEF^r \tag{8}$$

2.4. Data sources

Employing a full multi-regional input-output model with a high sector disaggregation, the Eora database provides a long time series of global economic input-output tables, from 1990 to 2013 [69,70]. In this work, the Eora database (latest Version 199.82) is applied as the basis to obtain the inter-sectoral input-output details for the world economy of 2012. The world economy is divided into 188 regions, each region with 26 sectors. Detailed information of the regions and sectors are listed respectively in Appendices A and B. The statistics of coal exploitation are mainly collected from the International Energy Agency (IEA) database [71]. The coal production volume in the 139 regions among the 188 regions are recorded by IEA, while for the other 49 regions, relevant data are considered ignorable. Given the fact that in statistics coal resources are generally exploited by the mining sector, regional coal exploitation data taken from IEA are allocated into Sector 3 (Mining and quarrying) of the corresponding region. As a porter or bridge between the systems of environment and economy, Sector 3 exploits primary coal resources from the environmental system and then supplies extracted or preliminarily processed coal as the sector's product to other sectors in the economic system.

3. Results

3.1. Coal resources embodied in final use

Overall, 1.62E + 08 TJ of coal resources are exploited from the environmental system and then embodied in final use activities of the economic system. Fig. 2 provides an overview of the six final use categories that are responsible for these resources depletion. At the

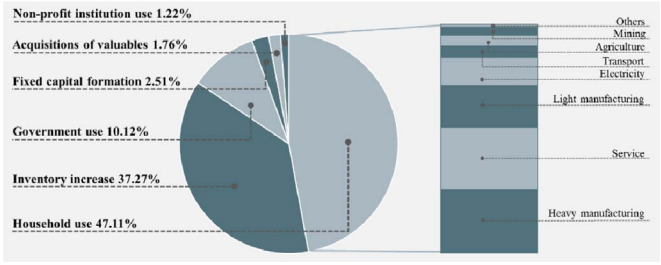

Fig. 2. Composition of coal embodied in final use for world economy.

global scale, 58.45% of coal use is related to the consumption activities of household, government and non-profit institution, among which household is the largest final user. 7.65E + 07 TJ of coal resources are embodied in household use, which has a direct relationship with the living condition on the globe. The sectoral pattern of household coal use is described in this figure to probe into the sectoral contribution to the residents' living consumption. The 26 sectors are aggregated for illustration purpose (see Appendix B). Heavy manufacturing contributes the largest percentage of 27.65%, followed by the sectors of service and light manufacturing. The electricity industry is treated as the main consumer of coal resources in traditional direct accounting, but from the embodiment viewpoint, coal use in the electric power generation ranks behind the manufacturing and service sectors due to the considerable indirect coal usage in the two sectors. Hence, in industrial structure adjustment towards saving coal resources and reducing pollutant emissions, both direct and indirect effects should be given fair consideration.

For the 188 regions investigated, coal resources embodied in their final use are indicated by *CEF* and are presented in Fig. 3 (numerical results are provided in Appendix C). Mainland China is by far the largest user of embodied coal with a *CEF* of 6.19E + 07 TJ, accounting for 38.10% of the world total use. It represents that 6.19E + 07 TJ of coal resources are exploited from the environmental system globally to sustain the consumption actives of households and governments, and the investment actives of enterprises in mainland China. The United States is the second largest user, followed by Japan, India and Indonesia.

For comparison, another two indices of *CED* (coal exploited directly) and *CCD* (coal consumed directly) are portrayed here. *CED* records the amount of coal resources mined directly within the region's territory, while *CCD* counts the amount of coal resources consumed directly by the region, including the coal for direct combustion and for non-energy use. IEA database [71] is applied as the basis for the statistics of *CED* and *CCD*. As shown in Fig. 3, the three indices are vastly different for each region. In contrast to the ordering based on the index of *CEF*, the five largest exploiters are mainland China, the United States, Indonesia, Australia and India regrading *CED*, and the five largest direct consumers are mainland China, the United States, India, Japan and Russia according to *CCD*. China's economy is now experiencing a rapid development with an increasing demand for energy resources. The abundant coal reserves in China therefore place coal the key position in domestic energy supply. Mainland China exploits 7.74E + 07 TJ of coal resources, representing nearly half of the world total coal exploitation. Because some of these coal resources are put into the international market by mainland China, 7.06E + 07 TJ of coal resources are counted to be consumed directly for local production. But not all the produced goods or services in mainland China are for its own final use. As the "world factory", mainland China provides lots of non-coal goods or services with local coal depletion to foreign regions for their final use. Such indirect coal use embodied in the non-coal goods or services is always ascribed to the producer rather than the consumer in the conventional direct consumption statistics, which leads to the transfer of responsibility from the consumer to the producer. Actually, the amount of coal resources finally used by mainland China is 20.08% and 12.41% less than that of its direct exploitation (*CED*) and direct consumption (*CCD*), respectively. India and Russia, being also two resource-based economies, show a similar performance as mainland China. On the contrary, the United States is witnessed to be in an opposite situation. *CEF* of the United States is 2.57E + 07 TJ, 23.92% larger than its *CED* and 51.87% larger than its *CCD*. For Japan and Germany, coal embodied in their final use are also way more than their exploitation and direct consumption. Especially, although Japan doesn't exploit coal in local area because of the poor reserve, Japan can also own the utility of coal resources through international trade. According to *CCD*, 3.75E + 06 TJ of coal consumption occurs in Japan. With the aid of the embodiment concept, however, 8.97E + 06 TJ of coal use is attributable to Japan, 2.39 times of its direct consumption. Hence, Japan takes a bigger responsibility for coal conservation from the consumer perspective than that from the producer perspective.

Natural resources are fundamental to social development. Each region in the world requires massive inputs of natural resources, especially energy resources to sustain its development. In context of globalization characterized by inter-regional trade, a region can easily obtain energy support directly and indirectly from foreign areas by importing energy products and energy-intensive products, and transfers the environmental burden related to energy mining and combustion to regions abroad. Although this importing region can gain a decline in local coal use as indicated by *CED* and *CCD*, the exporting regions have to pay for it, and the total amount of world coal use may remain constant or even increase. Different from *CED* and *CCD* in the direct accounting which merely consider the on-site immediate coal use, *CEF* also incorporates historical and off-site information, and thus provides us a global insight into the conservation work of coal resources.

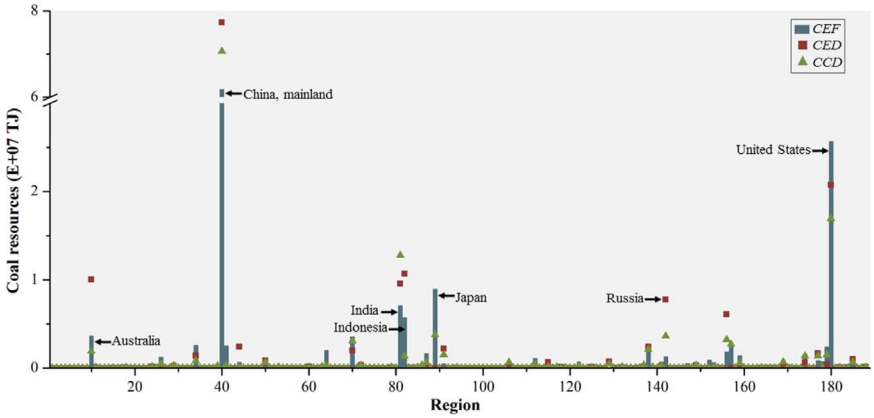

Fig. 3. *CEF* (coal embodied in final use), *CED* (coal exploited directly) and *CCD* (coal consumed directly) of the 188 regions (See Appendix A for details of the regions.).

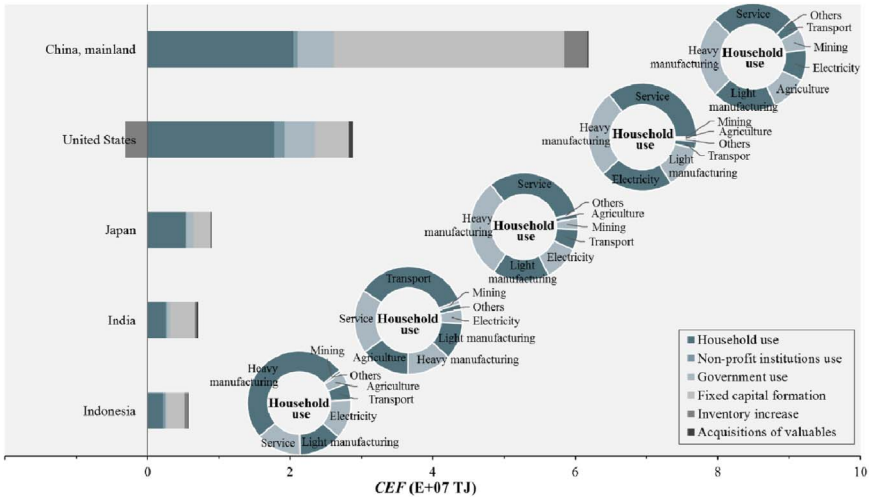

Fig. 4. Composition of *CEF* (coal embodied in final use) for the top 5 users.

Illustrated in Fig. 4 are the structures of *CEF* for the top 5 coal users. For mainland China,coal use for fixed capital formation takes up the largest share of 52.20% of the total use. The main reason behind this phenomenon is the large-scale infrastructure construction in China to back up its vigorous economy. Though the total coal use of mainland China is 2.41 times of that in the United States, household coal use in mainland China is only slight larger than that in the United States. For the 5 regions, a comparison of the proportions of household coal use in their respective total use yields an interesting result. In mainland China, 33.00% of its total coal use is for household consumption, while the ratio is 69.23% in the United States, 59.82% in Japan, 35.64% in India and 38.40% in Indonesia. The United States and Japan as two high-income nations with high living standard are found to pour most resources to household consumption activities. By contrast, the other three regions as the major emerging markets in the world all pay more attention to fix capital formation than household use. Compared with the world's household use structure in Fig. 2, the agriculture sector makes a greater contribution to household use in mainland China, revealing China's status as a big agriculture-intensive economy.

As household use has a close relation with the residents' consumption activities in the region, per-capita coal use embodied in household use is calculated based on the population data published by World Bank [72], to study the living standard in the 188 regions. As exhibited in Fig. 5, the per-capita coal use varies greatly among the 188 regions (numerical results are provided in Appendix C), manifesting an extremely unbalanced distribution of coal use worldwide and big disparity of living conditions in these regions. The maximum value appears in Hong Kong (1.51E-01 TJ/cap), while the minimum one is found in Belarus (1.14E-05 TJ/cap). The world average household use (shown by the dashed line) is calculated as 1.09E-02 TJ per capita. More than three fifths of the population (4.33 of 7.03 billion) from 117 regions fail to reach the global average level, which are mostly in middle- or low-income countries. The per-capita household coal use in mainland China is 1.51E-02 TJ/cap, only one-tenth of that in Hong Kong of China, indicating the huge gap between rich and poor in China. Moreover, mainland China as the largest final user of embodied coal, can only occupy the 57th place with respect to the per-capita household coal use. The embodied household coal use per people in mainland China is just a quarter of that of the second largest final user, the United States (5.67E-02 TJ/cap).

3.2. Coal resources associated with trades

As a consequence of the geographic disconnect between sources of inputs associated with coal production and sinks of final coal demand, coal resources are largely traded directly, and indirectly along with the non-coal commodities trade around the world. Taking both direct and indirect coal trade into account, *CEI* (coal embodied in imports) and *CEE* (coal embodied in exports) aim to give a panorama of the total coal transactions between the regions. At the global scale, the total trade volume of embodied coal is 1.15E + 08 TJ, in magnitude 70.85% of the world total exploitation. For the 188 regions, Fig. 6 shows the distribution of coal resources embodied in their imports and exports. The United States is the largest importer of embodied coal. It shows

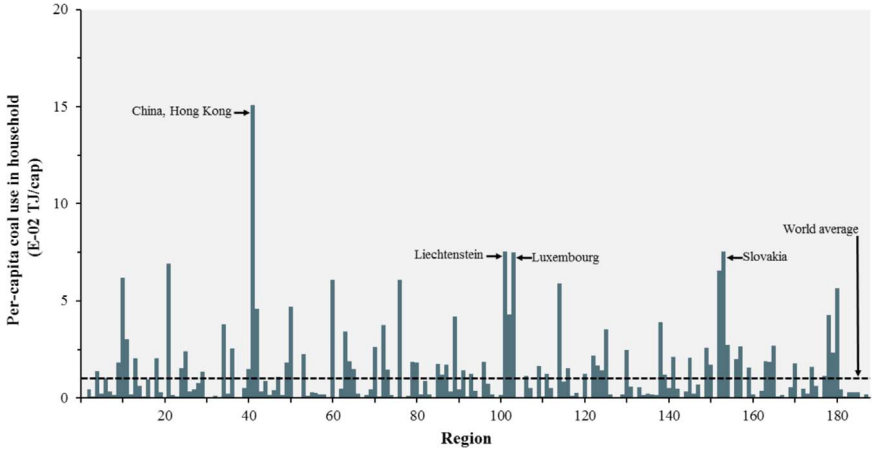

Fig. 5. Per-capita coal use embodied in household use of the 188 regions (See Appendix A for details of the regions.).

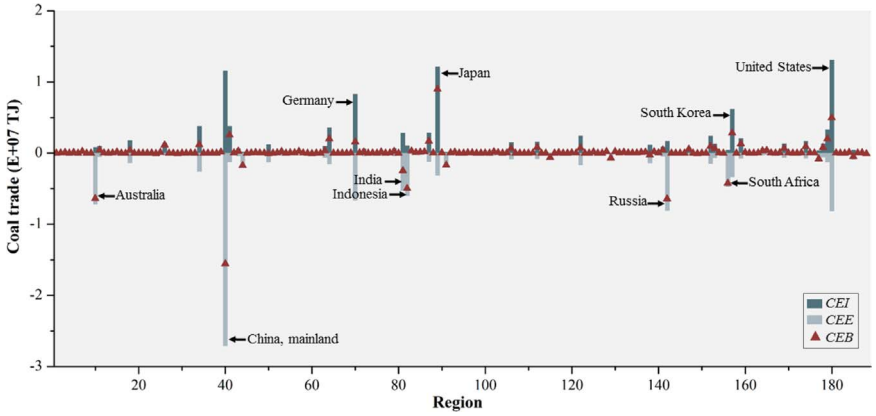

Fig. 6. *CEI* (coal embodied in imports), *CEE* (coal embodied in exports) and *CEB* (coal embodied in trade balance) of the 188 regions (See Appendix A for details of the regions.).

that 1.31E + 07 TJ of embodied coal is imported by the United States from foreign regions, nearly 50 times of its direct coal imports (2.74E + 05 TJ) [73]. As a main consuming nation, the United States imports a lot of coal resources or coal-intensive goods in inter-regional trade. A decline is found in the direct coal imports of the United States in recent years, but whether this decline can also be witnessed based on the embodied coal trade analysis needs further study. Japan is the second largest importer of embodied coal, followed by mainland China, Germany and South Korea. Regarding the embodied exports, mainland China, the United States, Russia, Australia and Germany rank top five. 2.71E + 07 TJ of embodied coal is exported by mainland China, which is 1.35 times larger than its imports. Conversely, the import of Japan is 2.85 times larger than the export. Accordingly, *CEB* (coal embodied in trade balance) is proposed to explore the region's trading pattern on the international scene.

The embodied coal resources in inter-regional net trade sum up to 4.67E + 07 TJ, above a quarter of the world total exploitation. As shown in Fig. 6, 165 regions have positive *CEB* with the embodied coal surplus, while the other 23 regions have negative value with the deficit. Japan is world's leading net importer of embodied coal with a *CEB* of 8.97E + 06 TJ. Due to the lack of coal resources in Japan, Japan relies completely upon foreign resources. In addition to Japan, the United States, South Korea, Hong Kong and France also have a considerable net coal import. It is noted that all the five net importing regions are high-income regions in the world. As the high-income regions tend to remove the energy-intensive industries to the middle- and low-income areas to reduce domestic energy use and protect local environment, inter-regional trade becomes the main way for them to gain the utility of energy resources. On the other hand, the top five largest net exporters are mainland China, Russia, Australia, Indonesia, and South Africa, which all have abundant coal reserves.

The major inter-regional trade flows of embodied coal are portrayed in Fig. 7(a). The whole world is divided into 20 regions in this figure, i.e., China (including the mainland, Hong Kong, Macao and Taiwan), Association of Southeast Asian Nations (ASEAN, including 10 member states), the European Union (EU27, including 27 member states, excluding Croatia, of the European Union), the top 16 largest exporters of embodied coal among the other 147 regions, and the one integrating the rest regions (ROW) together. The arc length represents the corresponding region's gross export volume of embodied coal, while the chord describes the trade volume between the two connected regions. China is the largest coal exporter among the 20 regions. 2.52E + 07 TJ of embodied coal is exported from China, of which 25.49% is to EU27, 18.79% to the United States, 14.73% to Japan, 10.14% to ASEAN and 8.37% to South Korea. ASEAN is the second largest coal exporter with an export volume of 8.25E + 06 TJ. The largest leaving

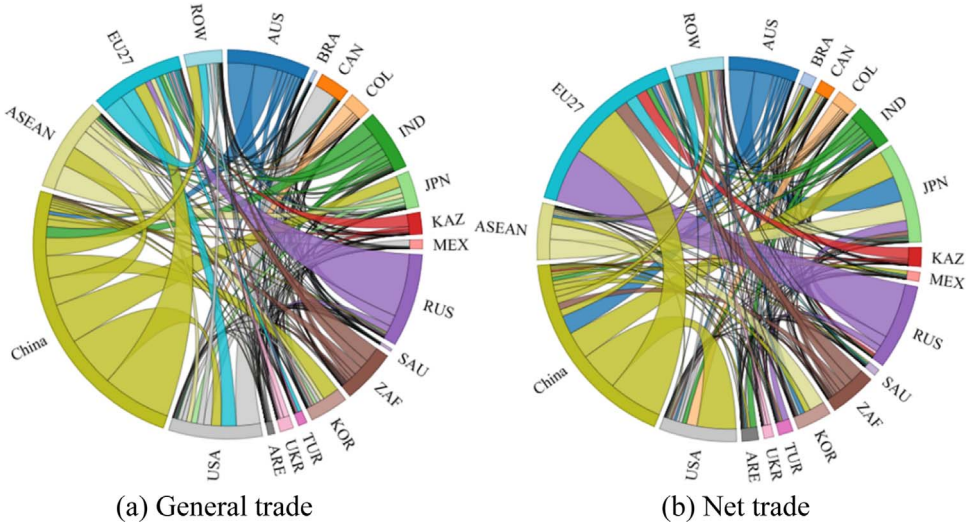

Fig. 7. Embodied coal connections between the 20 major economies by (a) general trades; (b) net trades (The China region includes the mainland, Hong Kong, Macao and Taiwan; ASEAN stands for Association of Southeast Asian Nations; 27member states, excluding Croatia, of the European Union are aggregated into one economy indicated asEU27; ROW refers to the rest of the world. The abbreviations of the other regions' names can be found in Appendix A. (a) The general trade relations between every two economies are portrayed by the chords. The different thicknesses at the two ends of the chord respectively represent the two connected economies' export volumes of embodied coal to each other. The chord's color corresponds to the larger exporter of the two. (b) The net trade relations between every two economies are portrayed by the chords. The thickness at both ends of the chord represents the net trade volume of embodied coal between the two connected economies. The chord's color corresponds to the net exporter.).

flow from ASEAN goes to Japan, followed by the flow to China and the flow to South Korea. As the largest economic entity in the world, EU27 imports large amounts of coal from other countries. Totally EU27 imports 2.11E + 07 TJ of embodied coal, making it the leading importer. Among its imports, 30.46% is from the China and 27.67% from Russia. Japan is also a main importer. China is the largest importing marker for Japan, and contributes 30.65% of Japan's total imports, followed by Australia and ASEAN with respective contributions of 20.64% and 19.68%.

In addition, the net trade relationships between the 20 regions are presented in Fig. 7(b). It can be seen that EU27 occupies a bigger part of the circle in this figure than in the figure regarding the general trade, which is attributed to its extremely imbalanced status in coal trade with other regions. The coal embodied in the imports of EU27 is calculated to be 2.62 times that in its exports. Russia is the major contributor to its trade imbalance. Its imports from Russia are 10.64 times larger than its exports to Russia. Hence, EU27 transfers the biggest environmental burden related to coal production to Russia. Similarly, China is found to be biggest receiver of the environmental pollution caused by the economic development in both the United States and Japan.

Given the growing concern about the energy and environmental issues in China and the United States, the geographic and sectoral patterns of the embodied coal trade of the two countries are investigated in further detail (see Fig. 8). Regions and sectors are aggregated with details that are shown in Appendix A and B, separately. The importing markets of China are mainly distributed in Asia Pacific. Of China's total imports, 71.28% is from Asia Pacific, led by Australia, 12.95% from Europe & Eurasia, 8.54% from North America, 6.76% from Africa, 0.57% from Middle East and 0.39% from South & Central America. On the sectoral level, the imports associated with the mining sector make up 49.17% of the total coal imports in China, indicating the similar share that the direct and indirect coal imports hold. For China, most imports from Asia Pacific and Africa are required by its mining industry, while the imports from Europe & Eurasia and North America mainly flow into the heavy manufacturing industry. In addition, the heavy industrial products constitute 64.89% of China's total coal exports, 3.42 times larger than the direct coal exports from the mining sector. These heavy industrial products are mainly exported to three markets of Asia Pacific, Europe & Eurasia and North America. Among China's exports to North America, only 3.43% are directly associated with the mining sector as direct coal trade, and the remaining 96.57% are embodied in the non-coal goods or service trade. Different from China's imports in which mining sector plays the most important role, the imports of the United States are mainly driven by the heavy manufacturing sector. Vast majority of 63.76% of heavy industrial products imports in the United States are from Asia Pacific, headed by China. South & Central America makes the biggest contribution to direct coal imports of the United States, in contrast to Asia Pacific as the largest importing market of embodied coal for the United States. For the exports from the United States, 51.44% are composed by the products from the heavy manufacturing industry, and 34.75% by the physical coal resources from the mining industry. Asia Pacific is the leading receiver of the heavy industrial products, while North America is the primary destination region for the physical coal resources.

3.3. Source-to-sink coal budget

The 188 regions as source regions exploit coal resources locally to obtain the utility of these resources. Then the utility of the resources is embodied in economic commodities entering the inter-regional trade and finally used by the 188 regions as sink regions. Hence, to explore the relations between the sources and sinks in global coal supply

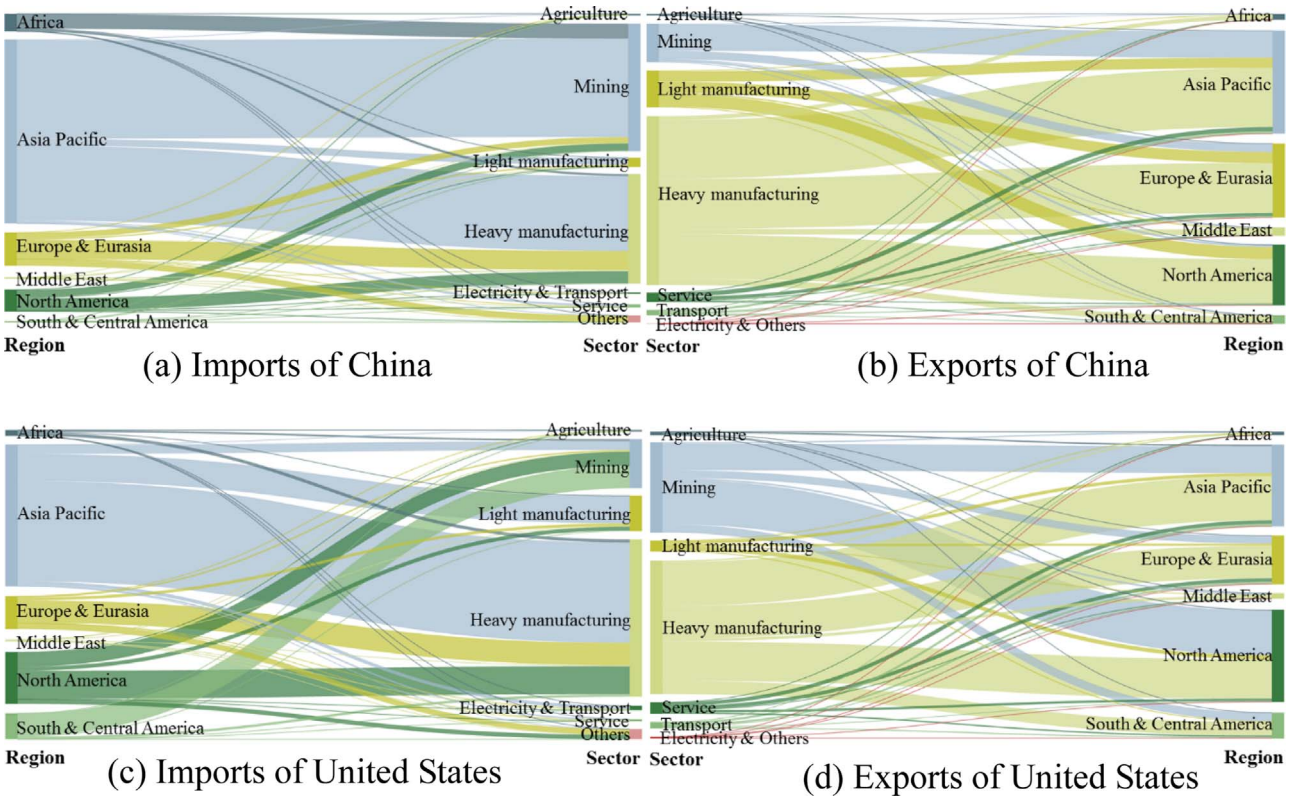

Fig. 8. Regional and sectoral contributions to coal trade embodied in (a) the imports of China; (b) the exports of China; (c) the imports of the United States and (d) the exports of the United States ((a) The geographic distribution of coal imports required by the sectors within China is described by the Sankey diagram. The thickness of the line represents the volume of coal resources flowing from the exporting region to the sector in China with a color corresponding to the region. (b) The sectoral structure of coal exports from China driven by foreign regions' demand is analyzed by the Sankey diagram. The thickness of the line represents the volume of coal resources exported by China's sector to the foreign region with a color corresponding to the sector. Similar to (a) and (b), (c) and (d) are drawn for the imports and exports of the United States, respectively.).

chains, all coal use flows are tracked from coal exploitation to final use to compile a source-to-sink budget. For the source regions, their self-sufficiency rates are presented in Fig. 9(a) to reveal the consumption distribution of local coal resources. For mainland China as the largest source region, its self-sufficiency rate is 70.74%, representing that about three-fourths of coal exploited in mainland China is used to meet local final demand, and one-fourth is finally used by foreign regions to support the economic development there. As mainland China is a big coal-consuming region, local requirements therefore become a priority issue. However, the vast majority of coal resources exploited in Russia are found to be putted into the global market to serve foreign regions. Russia as the sixth largest exploiter among the 188 regions, has an extremely low self-sufficiency rate of 2.89%. Russia is a typical resource-based nation with rich energy reserves, and its economy relies heavily on energy exports. So it exploits coal resources mainly for other regions' use rather than for its own use.

Parallel to γ_{source} that locates the destination of a region's coal resources in global coal supply chains, γ_{sink} is designed to trace the origin of coal resources used in the region. As shown in Fig. 9(b), mainland China owns the largest self-sufficiency rate of 88.52%, manifesting that 88.52% of coal requirements in mainland China is satisfied by local resources, and 11.48% is by foreign resources. For the United States as the second largest sink region, 59.09% of the coal resources embodied in its final use is provided by local areas. Therefore, it can be seen that the United States relies more on foreign coal than China. But according to the conventional external dependence degree of coal in national statistics, which is defined as the ratio of net coal imports over total coal consumption, the United States is reported with a negative dependence degree of − 16.54% [73], while China has a positive degree of 7.34% [74]. There is a huge difference between the results obtained by the two indices, and it is because that the conventional external dependence degree quantifies a region's dependence on foreign coal from the mathematical perspective, while the self-sufficiency rate tries to provide a physical view by clearly distinguishing between coal resources from different regions. To be specific, in the calculation of conventional external dependence degree, all coal resources exploited in a region are assumed to be used by the region itself, which cannot achieve in reality. So only coal resources that are exploited in the region and finally used by the region are taken as local contribution to final use in the self-sufficiency rate. As a result, the self-sufficiency rate for both the United States and China are in magnitude larger the corresponding conventional ratio. Moreover, the United States requires a lot of non-coal commodities from the international market, and these commodities produced in foreign regions need massive foreign coal inputs during their production processes. But the conventional external dependence degree fails to take these indirect foreign coal inputs embodied in traded commodities into consideration. In these regards, the self-sufficiency rate can provide a more precise way to evaluate the contribution of foreign coal to local consumption and offers us a deeper insight into the energy security.

A source-to-sink coal budget for the global coal supply chains is presented by a heatmap [75] in Fig. 10. The budget portrays the relationships between the 20 major source regions as coal exploiters (China, ASEAN, EU27 and the top 17 biggest coal exploiters among the other 147 regions) and the 20 sink regions as coal users (China, ASEAN, EU27 and the top 17 biggest coal users among the other 147 regions). The source regions exploit coal resources from local environment, and these resources are finally used by the sink regions. In the figure, the rows delineate the distribution of an exploiter's primary coal

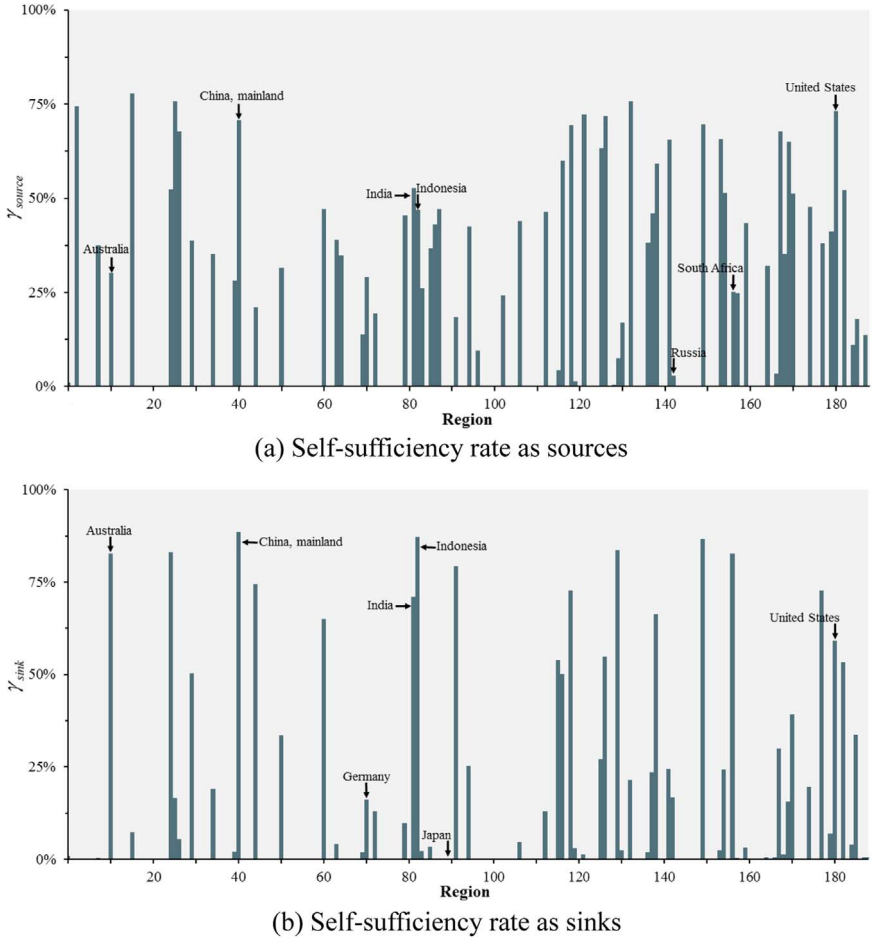

Fig. 9. Self-sufficiency rate of the 188 regions as (a) sources; (b) sinks (See Appendix A for details of the regions.).

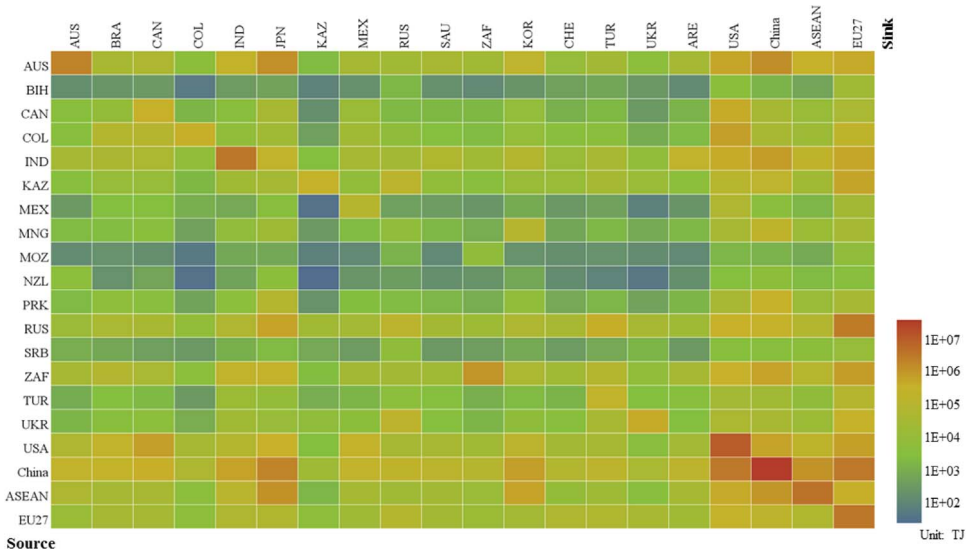

Fig. 10. Source-to-sink budget for global coal resources (The China region includes the mainland, Hong Kong, Macao and Taiwan; ASEAN stands for Association of Southeast Asian Nations; 27 member states, excluding Croatia of the European Union are aggregated into one economy indicated as EU27. The abbreviations of the other regions' names can be found in Appendix A. The heat map describes the relationships between the source regions and sink regions. The color in the box is related to the volume of coal resources that are extracted in the source region to meet the final demands of the sink region, and denary logarithm is adopted for presentation.).

resources through the global supply chains, and the columns enumerate the composition of embodied coal use required by a final user to maintain its development. The color changes from blue to red to represent the increase of coal requirements by the sink region from the source region. From the row point of view, China is the largest source region among the 20 regions, and produces 47.68% of the world total coal exploitation. 7.74E + 07 TJ of coal resources are exploited in China, of which 73.25% is consumed for its own final use, 6.32% for the United States, 6.16% for EU27, 3.79% for Japan, 2.17% for ASEAN and 8.31% for the other foreign regions in the world. The United States turns out to be the biggest foreign beneficiary of China's coal resources, so it would be the major victim if China ran into supply problems. From the column point of view, EU27 is the third largest sink region after China and the United States. 2.01E + 07 TJ of coal resources are embodied in EU27's final use, of which 25.70% is exploited in local environment, 23.78% is from China, 20.74% is from Russia, 5.53% is from South Africa, 4.93% is from the United States and 19.32% is from the other foreign regions. Hence, China and Russia are two main foreign suppliers of coal resources for EU27. What's more, 53.71% of Russia's coal resources is used by EU27, making EU27 the dominate receiver of Russian coal. Consequently, the European Union would suffer the biggest impact if Russia cut down the coal supply.

4. Discussions

4.1. Coal use from the embodiment perspective

According to IEA statistics, 49.91% of the world coal in 2012 is used in the power station [71]. The electricity industry is therefore always regarded as the biggest coal user based on the traditional direct coal accounting principle. What is overlooked, however, is that 42.34% of electricity generated by the power station is used for industrial production. The industrial sector is in fact a main indirect coal user. In Fig. 2 above, both direct and indirect coal use as distinctive components of embodied coal use is described for the sectors, and the heavy manufacturing industry is shown to make the biggest contribution to the global household coal use, 1.25 times larger than the electricity industry. The existing policies regarding coal use reduction mainly concentrate on the major direct coal users, like power industry, and the indirect coal users aren't given sufficient attention. The present embodiment research is to supplement conventional direct coal accounting and provides basic reference for industrial structure adjustment from a systems perspective.

At the national scale, the United Kingdom is reported to obtain certain achievements in the movement away from coal. Last year, the

Table 1
Comparison with previous embodiment studies.

	Chen and Chen [68]	Tang et al. [40]	Cortés-Borda et al. [41]	Cortés-Borda et al. [42]	This study
Object	Embodied energy, including coal, crude oil, natural gas, hydropower, and nuclear power	Embodied oil	Embodied solar energy	Embodied nuclear energy	Embodied coal
Year	2004	1997–2007	1995–2009	1995–2009	2012
Input-output database	GTAP, including 112 regions and 57 sectors	The table released by Chinese government	WIOD, including 40 regions and 35 sectors	WIOD, including 40 regions and 35 sectors	Eora, including 188 regions and 26 sectors
Largest producer	United States	Not available	China	United States	Mainland China
Largest consumer/user	United States	Not available	China	United States	Mainland China
The share of resources use embodied in trade	41.34%	Not available	7% in 2008	3.4% in 2006	70.85%
Largest importer	United States	Not available	Not available	Belgium	United States
Largest net importer	United States	Not available	United States	Italy	Japan
Largest exporter	Mainland China	Not available	Not available	France	Mainland China
Largest net exporter	Mainland China	Not available	China	France	Mainland China
China's role in international trade	Net exporter	Net exporter	Net exporter	Net importer	Net exporter

direct coal use in the United Kingdom fell back to the level 200 years ago [76]. Coal is witnessed to leave the stage of the country. However, from the embodiment perspective, the coal use in the United Kingdom shows a different scene. The United Kingdom ranks in the 11th place among the 188 regions by the indicator of *CEF*. The per-capita household coal use in the United Kingdom is even 55.17% larger than that in mainland China. The main reason behind is the massive imports of the country. The direct coal consumption in the United Kingdom has been cut down greatly in recent years, but a considerable amount of indirect coal use is associated with the commodities and services imported by this country. 3.31E + 06 TJ of embodied coal is imported by the United Kingdom, in magnitude 2.85 times of its direct coal import [71]. In the process of energy transformation, the high-income countries tend to transfer their dirty energy use to the foreign areas.

4.2. Coal use embodied in trade

The total amount of coal use embodied in international trade is revealed in magnitude up to about three-quarters of the world total of coal exploitation. Mainland China is both the largest exporter and the largest net exporter in the embodied coal trade. Coal combustion is regarded as a major source of carbon emissions. As the biggest coal user in the world, China has therefore been under huge pressure in the international climate negotiation. But it should be noted that not all the coal use in China is to satisfy the needs of local development. Massive embodied coal resources are exported by China along with the export of commodities labeled 'Made in China'. In total, 2.71E + 07 TJ of embodied coal is exported by mainland China, above one-third of its total exploitation.

Shown in Table 1 is a comparison with some previous embodiment studies on various energy sources. When all energy sources, including coal, crude oil, natural gas, nuclear energy and so on, are considered together in the embodied energy analysis, China still plays the role of net exporter [68]. But if the energy sources are examined one by one, China's role in international trade varies. In the embodied trade of both crude oil [40] and solar energy [41], China acts as a net exporter, but for nuclear energy [42], China becomes a net importer. The share of nuclear energy within total energy in China is merely 1.58%, one-third of the world average level [76]. Hence, the import of China from foreign areas involves more nuclear energy use. China has taken coal resources as its main source of energy to fuel the industrialization. The share of coal in China reaches 61.83%, above twice the world average [76]. Hence, in the outflow of energy resources in terms of embodied energy in exports, coal also takes the dominant proportion. The issue of energy becomes more complicated due to the increasing massive indirect coal exports.

5. Conclusion

As an affordable and widely distributed primary energy resource, coal plays a critical role in sustaining our modern society. But due to the growing concern about climate change, the use of coal has become a controversial issue and has aroused extensive attention. The prevalent researches on coal merely focus on the direct coal use and the direct pollution induced by the direct use, and fail to take account of the indirect coal use which is related to the use of commodities or services that require coal inputs during their production processes. With the enhancement of the economic globalization, the indirect coal use embodied in the traded goods is witnessed increasingly important, resulting in the highly remarkable inter-regional leakage of environmental emissions. Hence, the present paper aims to provide a comprehensive overview of global coal use for the first time, with both the direct and indirect coal use taken into consideration. The world economy is simulated as a 188-region, 26-sector coupled network and a systems multi-regional input-output model is adopted to explore the connections from the source of coal exploitation to the sink of final use through supply chains in inter-regional trade.

For the world as a whole, nearly sixty percent of coal exploited is related to the consumption activities of household, government and non-profit institution, and the remainder is used for inventory, capital formation and acquisition activities worldwide. The coal use in household shows the biggest dependence on the industry of heavy manufacturing, instead of on the electricity industry which is generally supposed as the main coal consumer in the traditional direct accounting. For each region, the direct coal exploitation, the direct coal consumption and the total coal requirement are compared and discussed. Mainland China, the United States, Japan, India and Indonesia are found to be the five largest final users of embodied coal, in contrast to mainland China, the United States, Indonesia, Australia and India as the top five coal exploiters, and mainland China, the United States, India, Japan and Russia as the top five direct coal consumers. The United Kingdom is reported to approach the coal-free society, but the embodied coal indicators point out that the per-capita household coal use in the country is three-fifths larger than that in mainland China, the largest coal user in the world. The present embodiment research depicts a picture of the embodied coal consumption distribution for the world, which can contribute to recent efforts to better understand the role and responsibility of each country or region in the world coal market.

The global trade volume of embodied coal amounts up to seventy percent of the total coal exploitation in magnitude. The United States is recognized as the world's biggest embodied coal importer, while mainland China is the biggest exporter. The high-income regions tend to be net coal importers, while the middle- and low-income regions are net coal exporters, revealing the transfer of coal use in inter-regional trade. The direct and indirect coal imports occupy an equal share in the total imports of mainland China, while the United States' imports are dominated by non-coal products as indirect coal imports. Two new indicators of self-sufficiency rates are developed to track the destination and origin of coal resources in global coal supply chains, respectively. For the United States, two-fifths of coal required in its final use is from foreign areas, vastly different from the published value based on the conventional external dependence degree. The new indicators can be essential in policy making to enhance coal supply security.

As coal is now regarded as the leading source of greenhouse gases and atmospheric pollutions, results in the present study can also provide significant implications for climate and environmental protection policy. With the aid of international trade, coal use and related pollution can be easily transferred from consumers to producers, and the total amounts of world coal use and of world carbon emissions can even increase. In this regard, regional coal regulation in isolation can make little sense to energy conservation and carbon mitigation in context of globalization. This global overview is to shed light from regional and global perspectives.

Acknowledgements

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Appendix A

See appendix Table A1.

Table A1
Regions included in world economic input-output table.

	Region	Abbr.	Region grouping		Region	Abbr.	Region grouping
1	Afghanistan	AFG	Europe & Eurasia	42	China, Macao SAR	MAC	Asia Pacific
2	Albania	ALB	Europe & Eurasia	43	China, Taiwan	TWN	Asia Pacific
3	Algeria	DZA	Africa	44	Colombia	COL	South & Central America
4	Andorra	AND	Europe & Eurasia	45	Congo	COG	Africa
5	Angola	AGO	Africa	46	Costa Rica	CRI	South & Central America
6	Antigua	ATG	South & Central America	47	Croatia	HRV	Europe & Eurasia
7	Argentina	ARG	South & Central America	48	Cuba	CUB	South & Central America
8	Armenia	ARM	Europe & Eurasia	49	Cyprus	CYP	Middle East
9	Aruba	ABW	South & Central America	50	Czech Republic	CZE	Europe & Eurasia
10	Australia	AUS	Asia Pacific	51	Cote dIvoire	CIV	Africa
11	Austria	AUT	Europe & Eurasia	52	DR Congo	COD	Africa
12	Azerbaijan	AZE	Europe & Eurasia	53	Denmark	DNK	Europe & Eurasia
13	Bahamas	BHS	South & Central America	54	Djibouti	DJI	Africa
14	Bahrain	BHR	Middle East	55	Dominican Republic	DOM	South & Central America
15	Bangladesh	BGD	Asia Pacific	56	Ecuador	ECU	South & Central America
16	Barbados	BRB	South & Central America	57	Egypt	EGY	Africa
17	Belarus	BLR	Europe & Eurasia	58	El Salvador	SLV	South & Central America
18	Belgium	BEL	Europe & Eurasia	59	Eritrea	ERI	Africa
19	Belize	BLZ	South & Central America	60	Estonia	EST	Europe & Eurasia
20	Benin	BEN	Africa	61	Ethiopia	ETH	Africa
21	Bermuda	BMU	Europe & Eurasia	62	Fiji	FJI	Asia Pacific
22	Bhutan	BTN	Europe & Eurasia	63	Finland	FIN	Europe & Eurasia
23	Bolivia	BOL	South & Central America	64	France	FRA	Europe & Eurasia
24	Bosnia and Herzegovina	BIH	Europe & Eurasia	65	French Polynesia	PYF	Europe & Eurasia
25	Botswana	BWA	Africa	66	Gabon	GAB	Africa
26	Brazil	BRA	South & Central America	67	Gambia	GMB	Africa
27	British Virgin Islands	VGB	Europe & Eurasia	68	Gaza Strip	PSE	Middle East
28	Brunei	BRN	Asia Pacific	69	Georgia	GEO	Europe & Eurasia
29	Bulgaria	BGR	Europe & Eurasia	70	Germany	DEU	Europe & Eurasia
30	Burkina Faso	BFA	Africa	71	Ghana	GHA	Africa
31	Burundi	BDI	Africa	72	Greece	GRC	Europe & Eurasia
32	Cambodia	KHM	Asia Pacific	73	Greenland	GRL	North America
33	Cameroon	CMR	Africa	74	Guatemala	GTM	South & Central America
34	Canada	CAN	North America	75	Guinea	GIN	Africa
35	Cape Verde	CPV	Africa	76	Guyana	GUY	South & Central America
36	Cayman Islands	CYM	South & Central America	77	Haiti	HTI	South & Central America
37	Central African Republic	CAF	Africa	78	Honduras	HND	South & Central America
38	Chad	TCD	Africa	79	Hungary	HUN	Europe & Eurasia
39	Chile	CHL	South & Central America	80	Iceland	ISL	Europe & Eurasia
40	China, Mainland	CHN	Asia Pacific	81	India	IND	Europe & Eurasia
41	China, Hong Kong	HKG	Asia Pacific	82	Indonesia	IDN	Asia Pacific
83	Iran	IRN	Middle East	126	Nicaragua	NIC	South & Central America
84	Iraq	IRQ	Middle East	127	Niger	NER	Africa
85	Ireland	IRL	Europe & Eurasia	128	Nigeria	NGA	Africa
86	Israel	ISR	Middle East	129	North Korea	PRK	Asia Pacific
87	Italy	ITA	Europe & Eurasia	130	Norway	NOR	Europe & Eurasia
88	Jamaica	JAM	South & Central America	131	Oman	OMN	Middle East
89	Japan	JPN	Asia Pacific	132	Pakistan	PAK	Middle East
90	Jordan	JOR	Middle East	133	Panama	PAN	South & Central America
91	Kazakhstan	KAZ	Europe & Eurasia	134	Papua New Guinea	PNG	Asia Pacific
92	Kenya	KEN	Africa	135	Paraguay	PRY	South & Central America
93	Kuwait	KWT	Middle East	136	Peru	PER	South & Central America
94	Kyrgyzstan	KGZ	Europe & Eurasia	137	Philippines	PHL	Asia Pacific
95	Laos	LAO	Asia Pacific	138	Poland	POL	Europe & Eurasia
96	Latvia	LVA	Europe & Eurasia	139	Portugal	PRT	Europe & Eurasia
97	Lebanon	LBN	Middle East	140	Qatar	QAT	Middle East
98	Lesotho	LSO	Africa	141	Romania	ROU	Europe & Eurasia
99	Liberia	LBR	Africa	142	Russia	RUS	Europe & Eurasia
100	Libya	LBY	Africa	143	Rwanda	RWA	Africa
101	Liechtenstein	LIE	Europe & Eurasia	144	Samoa	WSM	Asia Pacific
102	Lithuania	LTU	Europe & Eurasia	145	San Marino	SMR	Europe & Eurasia
103	Luxembourg	LUX	Europe & Eurasia	146	Sao Tome and Principe	STP	Africa
104	Madagascar	MDG	Africa	147	Saudi Arabia	SAU	Middle East
105	Malawi	MWI	Africa	148	Senegal	SEN	Africa
106	Malaysia	MYS	Asia Pacific	149	Serbia	SRB	Europe & Eurasia
107	Maldives	MDV	Europe & Eurasia	150	Seychelles	SYC	Africa
108	Mali	MLI	Africa	151	Sierra Leone	SLE	Africa
109	Malta	MLT	Europe & Eurasia	152	Singapore	SGP	Asia Pacific

(continued on next page)

Table A1 *(continued)*

	Region	Abbr.	Region grouping		Region	Abbr.	Region grouping
110	Mauritania	MRT	Africa	153	Slovakia	SVK	Europe & Eurasia
111	Mauritius	MUS	Africa	154	Slovenia	SVN	Europe & Eurasia
112	Mexico	MEX	North America	155	Somalia	SOM	Africa
113	Moldova	MDA	Europe & Eurasia	156	South Africa	ZAF	Africa
114	Monaco	MCO	Europe & Eurasia	157	South Korea	KOR	Asia Pacific
115	Mongolia	MNG	Europe & Eurasia	158	South Sudan	SDS	Africa
116	Montenegro	MNE	Europe & Eurasia	159	Spain	ESP	Europe & Eurasia
117	Morocco	MAR	Africa	160	Sri Lanka	LKA	Europe & Eurasia
118	Mozambique	MOZ	Africa	161	Sudan	SUD	Africa
119	Myanmar	MMR	Asia Pacific	162	Suriname	SUR	South & Central America
120	Namibia	NAM	Africa	163	Swaziland	SWZ	Africa
121	Nepal	NPL	Europe & Eurasia	164	Sweden	SWE	Europe & Eurasia
122	Netherlands	NLD	Europe & Eurasia	165	Switzerland	CHE	Europe & Eurasia
123	Netherlands Antilles	ANT	Europe & Eurasia	166	Syria	SYR	Middle East
124	New Caledonia	NCL	Asia Pacific	167	Tajikistan	TJK	Europe & Eurasia
125	New Zealand	NZL	Asia Pacific	168	Tanzania	TZA	Africa
169	Thailand	THA	Asia Pacific	179	UK	GBR	Europe & Eurasia
170	TFYR Macedonia	MKD	Europe & Eurasia	180	USA	USA	North America
171	Togo	TGO	Africa	181	Uruguay	URY	South & Central America
172	Trinidad and Tobago	TTO	South & Central America	182	Uzbekistan	UZB	Europe & Eurasia
173	Tunisia	TUN	Africa	183	Vanuatu	VUT	Asia Pacific
174	Turkey	TUR	Europe & Eurasia	184	Venezuela	VEN	South & Central America
175	Turkmenistan	TKM	Europe & Eurasia	185	Viet Nam	VNM	Asia Pacific
176	Uganda	UGA	Africa	186	Yemen	YEM	Middle East
177	Ukraine	UKR	Europe & Eurasia	187	Zambia	ZMB	Africa
178	UAE	ARE	Middle East	188	Zimbabwe	ZWE	Africa

Appendix B

See appendix Table B1.

Table B1
Sectoral embodied intensity of coal resources for world economy.

Sector code	Sector content	Sector grouping
1	Agriculture	Agriculture
2	Fishing	Agriculture
3	Mining and quarrying	Mining
4	Food and beverages	Light manufacturing
5	Textiles and wearing apparel	Light manufacturing
6	Wood and paper	Light manufacturing
7	Petroleum, chemical and non-metallic mineral products	Heavy manufacturing
8	Metal products	Heavy manufacturing
9	Electrical and machinery	Heavy manufacturing
10	Transport equipment	Heavy manufacturing
11	Other manufacturing	Light manufacturing
12	Recycling	Light manufacturing
13	Electricity, gas and water	Electricity
14	Construction	Service
15	Maintenance and repair	Service
16	Wholesale trade	Service
17	Retail trade	Service
18	Hotels and restaurants	Service
19	Transport	Transport
20	Post and telecommunications	Service
21	Financial intermediation and business activities	Service
22	Public administration	Service
23	Education, health and other services	Service
24	Private households	Service
25	Others	Others
26	Re-export and re-import	Others

Appendix C

See appendix Table C1.

Table C1
Regional embodied inventory of coal resources.

Region	Coal resources in final use		Coal resources in trades		
	CEF	Household use	*CEI*	*CEE*	*CEB*
	(TJ)	(TJ/cap)	(TJ)	(TJ)	(TJ)
Afghanistan	1.31E + 04	2.57E − 04	1.35E + 04	4.00E + 02	1.31E + 04
Albania	2.72E + 04	4.54E − 03	3.13E + 04	4.15E + 03	2.72E + 04
Algeria	1.15E + 05	8.86E − 04	1.54E + 05	3.88E + 04	1.15E + 05
Andorra	2.35E + 03	1.40E − 02	2.83E + 03	4.75E + 02	2.35E + 03
Angola	1.10E + 05	2.42E − 03	1.45E + 05	3.50E + 04	1.10E + 05
Antigua	1.89E + 03	1.02E − 02	2.33E + 03	4.43E + 02	1.89E + 03
Argentina	2.61E + 05	3.40E − 03	3.34E + 05	7.57E + 04	2.58E + 05
Armenia	7.94E + 03	1.44E − 03	9.72E + 03	1.78E + 03	7.94E + 03
Aruba	4.35E + 03	1.83E − 02	7.98E + 03	3.63E + 03	4.35E + 03
Australia	3.67E + 06	6.21E − 02	8.17E + 05	7.20E + 06	− 6.38E + 06
Austria	4.64E + 05	3.02E − 02	1.00E + 06	5.39E + 05	4.64E + 05
Azerbaijan	3.58E + 04	1.77E − 03	5.00E + 04	1.42E + 04	3.58E + 04
Bahamas	1.35E + 04	2.04E − 02	1.74E + 04	3.90E + 03	1.35E + 04
Bahrain	2.38E + 04	6.11E − 03	3.59E + 04	1.21E + 04	2.38E + 04
Bangladesh	1.85E + 05	6.64E − 04	1.99E + 05	3.18E + 04	1.67E + 05
Barbados	5.66E + 03	9.50E − 03	6.98E + 03	1.33E + 03	5.66E + 03
Belarus	1.50E + 03	1.14E − 05	1.17E + 05	1.43E + 05	− 2.58E + 04
Belgium	4.24E + 05	2.06E − 02	1.80E + 06	1.38E + 06	4.24E + 05
Belize	2.12E + 03	2.93E − 03	2.90E + 03	7.85E + 02	2.12E + 03
Benin	4.43E + 03	2.26E − 04	4.76E + 03	3.32E + 02	4.43E + 03
Bermuda	7.63E + 03	6.92E − 02	8.46E + 03	8.25E + 02	7.63E + 03
Bhutan	3.43E + 03	1.68E − 03	4.81E + 03	1.38E + 03	3.43E + 03
Bolivia	1.89E + 04	9.04E − 04	2.36E + 04	4.71E + 03	1.89E + 04
Bosnia and Herzegovina	1.05E + 05	1.53E − 02	2.32E + 04	8.48E + 04	− 6.16E + 04
Botswana	1.58E + 05	2.43E − 02	1.42E + 05	1.91E + 04	1.23E + 05
Brazil	1.27E + 06	3.53E − 03	1.44E + 06	2.76E + 05	1.16E + 06
British Virgin Islands	1.27E + 03	4.43E − 03	2.10E + 03	8.23E + 02	1.27E + 03
Brunei	1.13E + 04	7.85E − 03	1.88E + 04	7.52E + 03	1.13E + 04
Bulgaria	1.81E + 05	1.35E − 02	1.69E + 05	2.24E + 05	− 5.41E + 04
Burkina Faso	8.94E + 03	2.39E − 04	9.57E + 03	6.30E + 02	8.94E + 03
Burundi	3.00E + 03	1.49E − 04	3.44E + 03	4.47E + 02	3.00E + 03
Cambodia	3.08E + 04	1.18E − 03	3.70E + 04	6.21E + 03	3.08E + 04
Cameroon	1.49E + 04	3.33E − 04	1.65E + 04	1.56E + 03	1.49E + 04
Canada	2.60E + 06	3.80E − 02	3.79E + 06	2.60E + 06	1.19E + 06
Cape Verde	2.63E + 03	2.38E − 03	3.14E + 03	5.12E + 02	2.63E + 03
Cayman Islands	2.78E + 03	2.56E − 02	3.37E + 03	5.86E + 02	2.78E + 03
Central African Republic	1.52E + 03	1.79E − 04	1.79E + 03	2.74E + 02	1.52E + 03
Chad	2.67E + 03	7.75E − 05	3.25E + 03	5.79E + 02	2.67E + 03
Chile	1.71E + 05	5.35E − 03	2.39E + 05	8.05E + 04	1.59E + 05
China, Mainland	6.19E + 07	1.51E − 02	1.16E + 07	2.71E + 07	− 1.55E + 07
China, Hong Kong	2.55E + 06	1.51E − 01	3.80E + 06	1.26E + 06	2.55E + 06
China, Macao	6.19E + 04	4.59E − 02	8.79E + 04	2.61E + 04	6.19E + 04
China, Taiwan	2.75E + 05	3.35E − 03	6.57E + 05	3.82E + 05	2.75E + 05
Colombia	6.85E + 05	8.70E − 03	2.03E + 05	1.94E + 06	− 1.74E + 06
Congo	1.53E + 04	1.47E − 03	2.19E + 04	6.66E + 03	1.53E + 04
Costa Rica	3.86E + 04	4.23E − 03	5.37E + 04	1.51E + 04	3.86E + 04
Croatia	9.06E + 04	1.11E − 02	1.50E + 05	5.91E + 04	9.06E + 04
Cuba	4.13E + 04	1.58E − 03	4.40E + 04	2.63E + 03	4.13E + 04
Cyprus	3.96E + 04	1.83E − 02	4.76E + 04	7.95E + 03	3.96E + 04
Czech Republic	8.12E + 05	4.72E − 02	1.23E + 06	1.29E + 06	− 5.35E + 04
Cote dIvoire	1.39E + 04	3.44E − 04	1.78E + 04	3.96E + 03	1.39E + 04
DR Congo	6.73E + 04	5.60E − 04	7.54E + 04	8.05E + 03	6.73E + 04
Denmark	2.38E + 05	2.28E − 02	5.11E + 05	2.73E + 05	2.38E + 05
Djibouti	2.52E + 03	1.36E − 03	3.21E + 03	6.90E + 02	2.52E + 03
Dominican Republic	5.49E + 04	3.17E − 03	6.84E + 04	1.35E + 04	5.49E + 04
Ecuador	6.71E + 04	2.49E − 03	8.01E + 04	1.30E + 04	6.71E + 04
Egypt	2.62E + 05	1.95E − 03	3.30E + 05	6.82E + 04	2.62E + 05
El Salvador	2.43E + 04	2.04E − 03	2.92E + 04	4.97E + 03	2.43E + 04
Eritrea	1.65E + 03	1.27E − 04	2.10E + 03	4.54E + 02	1.65E + 03
Estonia	1.23E + 05	6.08E − 02	8.54E + 04	1.32E + 05	− 4.63E + 04
Ethiopia	1.42E + 04	7.20E − 05	2.18E + 04	7.59E + 03	1.42E + 04
Fiji	8.88E + 03	4.67E − 03	1.12E + 04	2.29E + 03	8.88E + 03
Finland	3.88E + 05	3.43E − 02	9.79E + 05	6.32E + 05	3.47E + 05
France	2.03E + 06	1.89E − 02	3.60E + 06	1.57E + 06	2.02E + 06

(continued on next page)

Table C1 *(continued)*

Region	Coal resources in final use		Coal resources in trades		
	CEF	Household use	*CEI*	*CEE*	*CEB*
	(TJ)	(TJ/cap)	(TJ)	(TJ)	(TJ)
French Polynesia	7.32E + 03	1.49E – 02	8.02E + 03	6.97E + 02	7.32E + 03
Gabon	8.89E + 03	2.25E – 03	1.04E + 04	1.53E + 03	8.89E + 03
Gambia	1.52E + 03	4.47E – 04	1.71E + 03	1.84E + 02	1.52E + 03
Gaza Strip	1.31E + 04	1.45E – 03	1.37E + 04	6.54E + 02	1.31E + 04
Georgia	3.20E + 04	4.55E – 03	4.09E + 04	1.34E + 04	2.75E + 04
Germany	3.57E + 06	2.62E – 02	8.27E + 06	6.69E + 06	1.58E + 06
Ghana	5.13E + 04	8.68E – 04	5.88E + 04	7.48E + 03	5.13E + 04
Greece	5.07E + 05	3.74E – 02	5.80E + 05	4.09E + 05	1.70E + 05
Greenland	2.08E + 03	1.48E – 02	2.72E + 03	6.39E + 02	2.08E + 03
Guatemala	3.71E + 04	1.42E – 03	4.65E + 04	9.46E + 03	3.71E + 04
Guinea	5.72E + 03	2.24E – 04	6.70E + 03	9.77E + 02	5.72E + 03
Guyana	1.66E + 05	6.07E – 02	1.66E + 05	4.13E + 02	1.66E + 05
Haiti	6.34E + 03	3.61E – 04	7.34E + 03	1.00E + 03	6.34E + 03
Honduras	2.06E + 04	1.28E – 03	2.64E + 04	5.76E + 03	2.06E + 04
Hungary	3.10E + 05	1.86E – 02	6.75E + 05	4.32E + 05	2.43E + 05
Iceland	1.39E + 04	1.84E – 02	1.84E + 04	4.49E + 03	1.39E + 04
India	7.12E + 06	2.05E – 03	2.83E + 06	5.29E + 06	– 2.47E + 06
Indonesia	5.76E + 06	8.96E – 03	1.06E + 06	6.01E + 06	– 4.96E + 06
Iran	3.49E + 05	2.02E – 03	3.65E + 05	4.58E + 04	3.20E + 05
Iraq	8.18E + 04	4.81E – 04	8.65E + 04	4.69E + 03	8.18E + 04
Ireland	1.47E + 05	1.74E – 02	3.57E + 05	2.23E + 05	1.34E + 05
Israel	2.12E + 05	1.22E – 02	3.32E + 05	1.21E + 05	2.11E + 05
Italy	1.68E + 06	1.73E – 02	2.87E + 06	1.19E + 06	1.67E + 06
Jamaica	1.78E + 04	3.42E – 03	2.04E + 04	2.58E + 03	1.78E + 04
Japan	8.97E + 06	4.20E – 02	1.21E + 07	3.15E + 06	8.97E + 06
Jordan	6.18E + 04	4.51E – 03	7.85E + 04	1.67E + 04	6.18E + 04
Kazakhstan	5.16E + 05	1.41E – 02	1.68E + 05	1.86E + 06	– 1.69E + 06
Kenya	6.14E + 04	6.54E – 04	7.27E + 04	1.13E + 04	6.14E + 04
Kuwait	1.36E + 05	1.26E – 02	1.53E + 05	1.69E + 04	1.36E + 05
Kyrgyzstan	2.98E + 04	3.68E – 03	3.01E + 04	1.80E + 04	1.21E + 04
Laos	6.38E + 03	4.30E – 04	7.47E + 03	1.09E + 03	6.38E + 03
Latvia	6.62E + 04	1.85E – 02	9.59E + 04	2.98E + 04	6.61E + 04
Lebanon	6.20E + 04	7.41E – 03	7.42E + 04	1.22E + 04	6.20E + 04
Lesotho	8.33E + 03	1.88E – 03	9.30E + 03	9.73E + 02	8.33E + 03
Liberia	2.28E + 03	2.49E – 04	4.19E + 03	1.92E + 03	2.28E + 03
Libya	2.56E + 04	1.65E – 03	4.10E + 04	1.54E + 04	2.56E + 04
Liechtenstein	5.55E + 03	7.54E – 02	8.36E + 03	2.81E + 03	5.55E + 03
Lithuania	1.89E + 05	4.31E – 02	4.74E + 05	2.86E + 05	1.88E + 05
Luxembourg	9.05E + 04	7.51E – 02	1.89E + 05	9.89E + 04	9.05E + 04
Madagascar	1.53E + 04	3.66E – 04	1.77E + 04	2.40E + 03	1.53E + 04
Malawi	1.76E + 04	5.50E – 04	2.00E + 04	2.43E + 03	1.76E + 04
Malaysia	7.36E + 05	1.14E – 02	1.51E + 06	8.49E + 05	6.58E + 05
Maldives	6.51E + 03	5.19E – 03	7.52E + 03	1.01E + 03	6.51E + 03
Mali	7.53E + 03	2.28E – 04	8.10E + 03	5.64E + 02	7.53E + 03
Malta	1.23E + 04	1.65E – 02	1.86E + 04	6.33E + 03	1.23E + 04
Mauritania	6.43E + 03	7.19E – 04	8.44E + 03	2.01E + 03	6.43E + 03
Mauritius	3.13E + 04	1.26E – 02	4.01E + 04	8.78E + 03	3.13E + 04
Mexico	1.13E + 06	5.01E – 03	1.61E + 06	8.00E + 05	8.12E + 05
Moldova	4.12E + 03	1.98E – 04	2.15E + 04	1.74E + 04	4.12E + 03
Monaco	4.31E + 03	5.90E – 02	5.93E + 03	1.62E + 03	4.31E + 03
Mongolia	5.51E + 04	8.55E – 03	3.50E + 04	6.47E + 05	– 6.12E + 05
Montenegro	1.97E + 04	1.52E – 02	1.25E + 04	9.23E + 03	3.22E + 03
Morocco	7.88E + 04	1.03E – 03	1.06E + 05	2.69E + 04	7.88E + 04
Mozambique	1.17E + 05	2.67E – 03	3.49E + 04	4.05E + 04	– 5.51E + 03
Myanmar	9.66E + 03	1.16E – 04	1.12E + 04	2.24E + 04	– 1.12E + 04
Namibia	6.02E + 04	1.23E – 02	7.85E + 04	1.83E + 04	6.02E + 04
Nepal	2.71E + 04	4.64E – 04	3.22E + 04	5.60E + 03	2.66E + 04
Netherlands	7.40E + 05	2.21E – 02	2.44E + 06	1.70E + 06	7.40E + 05
Netherlands Antilles	6.86E + 03	1.69E – 02	8.60E + 03	1.75E + 03	6.86E + 03
New Caledonia	8.50E + 03	1.43E – 02	1.02E + 04	1.66E + 03	8.50E + 03
New Zealand	2.81E + 05	3.54E – 02	2.95E + 05	1.34E + 05	1.60E + 05
Nicaragua	2.16E + 04	1.86E – 03	1.17E + 04	6.52E + 03	5.16E + 03
Niger	4.93E + 03	1.44E – 04	5.60E + 03	6.69E + 02	4.93E + 03
Nigeria	2.28E + 05	5.27E – 04	2.61E + 05	3.46E + 04	2.27E + 05
North Korea	6.73E + 04	1.89E – 03	1.57E + 04	7.03E + 05	– 6.87E + 05
Norway	2.49E + 05	2.49E – 02	3.60E + 05	1.45E + 05	2.14E + 05
Oman	5.52E + 04	6.00E – 03	7.99E + 04	2.48E + 04	5.52E + 04
Pakistan	1.83E + 05	6.07E – 04	1.66E + 05	3.52E + 04	1.31E + 05
Panama	4.10E + 04	5.39E – 03	5.73E + 04	1.63E + 04	4.10E + 04
Papua New Guinea	2.92E + 04	1.60E – 03	3.70E + 04	7.83E + 03	2.92E + 04
Paraguay	2.62E + 04	2.14E – 03	2.90E + 04	2.71E + 03	2.62E + 04

(continued on next page)

Table C1 *(continued)*

Region	Coal resources in final use		Coal resources in trades		
	CEF	Household use	*CEI*	*CEE*	*CEB*
	(TJ)	(TJ/cap)	(TJ)	(TJ)	(TJ)
Peru	1.29E + 05	1.89E − 03	1.46E + 05	2.32E + 04	1.22E + 05
Philippines	3.17E + 05	1.60E − 03	3.92E + 05	2.37E + 05	1.55E + 05
Poland	2.16E + 06	3.89E − 02	1.16E + 06	1.42E + 06	− 2.56E + 05
Portugal	2.04E + 05	1.20E − 02	2.71E + 05	6.65E + 04	2.04E + 05
Qatar	6.33E + 04	5.34E − 03	8.21E + 04	1.88E + 04	6.33E + 04
Romania	7.10E + 05	2.13E − 02	8.80E + 05	4.36E + 05	4.44E + 05
Russia	1.33E + 06	4.76E − 03	1.69E + 06	8.11E + 06	− 6.42E + 06
Rwanda	6.86E + 03	3.34E − 04	7.38E + 03	5.21E + 02	6.86E + 03
Samoa	1.28E + 03	3.52E − 03	1.75E + 03	4.61E + 02	1.28E + 03
San Marino	2.06E + 03	2.09E − 02	3.34E + 03	1.27E + 03	2.06E + 03
Sao Tome and Principe	8.66E + 02	2.40E − 03	1.38E + 03	5.11E + 02	8.66E + 02
Saudi Arabia	5.66E + 05	6.85E − 03	7.68E + 05	2.01E + 05	5.66E + 05
Senegal	1.32E + 04	4.98E − 04	1.46E + 04	1.39E + 03	1.32E + 04
Serbia	2.45E + 05	2.60E − 02	3.95E + 04	9.92E + 04	− 5.97E + 04
Seychelles	4.91E + 03	1.73E − 02	6.48E + 03	1.57E + 03	4.91E + 03
Sierra Leone	4.71E + 03	4.08E − 04	5.92E + 03	1.21E + 03	4.71E + 03
Singapore	9.44E + 05	6.54E − 02	2.42E + 06	1.47E + 06	9.44E + 05
Slovakia	6.65E + 05	7.54E − 02	1.33E + 06	6.84E + 05	6.42E + 05
Slovenia	9.66E + 04	2.74E − 02	1.46E + 05	9.54E + 04	5.08E + 04
Somalia	5.61E + 02	2.82E − 05	6.54E + 02	9.39E + 01	5.61E + 02
South Africa	1.87E + 06	2.01E − 02	4.56E + 05	4.70E + 06	− 4.24E + 06
South Korea	2.86E + 06	2.67E − 02	6.18E + 06	3.36E + 06	2.82E + 06
South Sudan	5.50E + 03	2.65E − 04	6.40E + 03	8.98E + 02	5.50E + 03
Spain	1.43E + 06	1.56E − 02	2.08E + 06	7.50E + 05	1.33E + 06
Sri Lanka	8.02E + 04	1.80E − 03	1.05E + 05	2.47E + 04	8.02E + 04
Sudan	8.32E + 02	1.18E − 05	8.59E + 02	2.66E + 01	8.32E + 02
Suriname	5.02E + 03	3.58E − 03	6.30E + 03	1.28E + 03	5.02E + 03
Swaziland	4.02E + 04	1.90E − 02	5.37E + 04	1.35E + 04	4.02E + 04
Sweden	3.44E + 05	1.86E − 02	6.45E + 05	3.07E + 05	3.38E + 05
Switzerland	3.90E + 05	2.69E − 02	6.25E + 05	2.35E + 05	3.90E + 05
Syria	4.71E + 04	9.61E − 04	5.52E + 04	1.66E + 04	3.86E + 04
Tajikistan	1.70E + 04	1.44E − 03	1.49E + 04	5.42E + 03	9.50E + 03
Tanzania	5.01E + 04	5.03E − 04	5.37E + 04	5.61E + 03	4.81E + 04
Thailand	9.08E + 05	5.48E − 03	1.34E + 06	6.55E + 05	6.89E + 05
TFYR Macedonia	6.83E + 04	1.80E − 02	6.31E + 04	4.70E + 04	1.61E + 04
Togo	5.60E + 03	4.48E − 04	6.98E + 03	1.38E + 03	5.60E + 03
Trinidad and Tobago	1.41E + 04	4.69E − 03	2.59E + 04	1.18E + 04	1.41E + 04
Tunisia	5.41E + 04	2.29E − 03	7.31E + 04	1.91E + 04	5.41E + 04
Turkey	1.59E + 06	1.60E − 02	1.67E + 06	7.39E + 05	9.35E + 05
Turkmenistan	6.09E + 04	6.38E − 03	8.17E + 04	2.07E + 04	6.09E + 04
Uganda	2.87E + 04	4.14E − 04	3.00E + 04	1.39E + 03	2.87E + 04
Ukraine	8.78E + 05	1.15E − 02	3.68E + 05	1.17E + 06	− 8.05E + 05
UAE	7.87E + 05	4.28E − 02	1.36E + 06	5.69E + 05	7.87E + 05
United Kingdom	2.44E + 06	2.35E − 02	3.31E + 06	1.29E + 06	2.02E + 06
United States	2.57E + 07	5.67E − 02	1.31E + 07	8.15E + 06	4.96E + 06
Uruguay	2.97E + 04	4.50E − 03	3.54E + 04	5.73E + 03	2.97E + 04
Uzbekistan	5.56E + 04	8.94E − 04	3.06E + 04	3.17E + 04	− 1.12E + 03
Vanuatu	1.69E + 03	2.98E − 03	2.36E + 03	6.70E + 02	1.69E + 03
Venezuela	1.81E + 05	3.04E − 03	2.07E + 05	8.98E + 04	1.17E + 05
Viet Nam	5.24E + 05	3.08E − 03	4.42E + 05	9.05E + 05	− 4.63E + 05
Yemen	2.78E + 04	5.27E − 04	3.18E + 04	3.98E + 03	2.78E + 04
Zambia	5.19E + 04	1.88E − 03	6.98E + 04	2.01E + 04	4.97E + 04
Zimbabwe	9.51E + 03	2.68E − 04	8.03E + 04	1.71E + 05	− 9.06E + 04

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